For this exercise we will be using the ExoPlex mass-radius-composition solver to try and determine the compositions of the TRAPPIST-1 planets. The mass and radius of the TRAPPIST-1 planets are some of the precise available (both measured to <10%) due to the nature of the TTV methods used to measure these properties.

Each group will be utilizing the same dataset and varying a different planetary parameter. To start here is the basic data available for the TRAPPIST-1 planets from Agol et al., 2021 (The Planetary Science Journal):

|  |  |  |  |
| --- | --- | --- | --- |
| **Planet** | Mass [Earth Masses] (+σ/-σ) | Radius [Earth Radii]  (+σ/-σ) | Density [Earth Density] (+σ/-σ) |
| TRAPPIST-1b | 1.374 (+0.069, -0.069) | 1.116 (+0.014, -0.012) | 0.987(+0.048, -0.050) |
| TRAPPIST-1c | 1.308 (+0.056, -0.056) | 1.097 (+0.014, -0.012) | 0.991 (+0.040, -0.043) |
| TRAPPIST-1d | 0.388 (+0.012, -0.012) | 0.788 (+0.011, -0.010) | 0.792 (+0.028, -0.030) |
| TRAPPIST-1e | 0.692 (+0.022, -0.022) | 0.92 (+0.013, -0.012) | 0.889 (+0.030, -0.033) |
| TRAPPIST-1f | 1.039 (+0.031, -0.031) | 1.045 (+0.013, -0.012) | 0.911 (+0.025, -0.029) |
| TRAPPIST-1g | 1.321 (+0.038, -0.038) | 1.129 (+0.015, -0.013) | 0.917 (+0.025, -0.029) |
| TRAPPIST-1h | 0.326 (+0.020, -0.020) | 0.755 (+0.014, -0.014) | 0.755 (+0.059, -0.055) |

Some useful values:

1 Earth mass = 5.97 \* 1024 kg

1 Earth radius = 6371 km

Earth Density: 5512 kg m-3 = 5.512 g/cc

ExoPlex Mantle Validity Range (all values by mole):

0.5 ≤ Si/Mg ≤ 2.0 (steps of 0.1)

0.02 ≤ Ca/Mg ≤ 0.1 (steps of 0.01)

0.04 ≤ Al/Mg ≤ 0.12 (steps of 0.01)

0.0 ≤ Mass Fraction FeO ≤ 0.20 (0.0 – 0.1 steps of 0.02, 0.15, 0.2)

1400 ≤ Mantle Potential Temperature ≤ 2000 Kelvin

For this exercise you will be changing a planetary compositional parameter and calculating what range of these parameters are consistent with the observed densities of the TRAPPIST-1 planets.

For each model, every parameter can be changed in MR\_Trappist.py.

All editing can be done in the text editor of your choice and a Jupyter notebook.

**Exploring Core Chemistry**

1. Begin by making sure you are in the ExoPlex/Examples folder in the terminal. (cd ExoPlex/Examples)
2. Let’s begin by building a planet. To do this you need only to decide a composition (providing values for CaMg, FeMg, Mantle temperature etc.) and how many depth slices you’d like to appear in the core, mantle and water layers (num\_core\_layers, num\_mantle\_layers and number\_h2o\_layers). Note that if you do not include a water layer, number\_h2o\_layers should be set to zero.
   1. Type **python MR\_Trappist.py** and press Return. A plot should appear that shows you the density, pressure, gravity and temperature profile within your planet. This is for a two-layer planet (mantle + core) with the same mass as TRAPPIST-1b and an Earth composition (note: no water). Write down the calculated radius for this mass and composition. This will be your baseline mass (for a T1b size planet).
      1. If you’d like to plot this again (minus gravity), open the Jupyter notebook Tutorial\_Plots.ipynb in a separate terminal. Open a second terminal, ssh into the AWS instance, cd ExoPlex/Examples, type jupyter notebook Tutorial\_Plots.ipynb. Follow the instructions.
   2. Now try changing things! Add water. Change FeMg and SiMg. Each time you change something, rerun python MR\_Trappist.py and see if you notice any changes. Compare your plots with those from others within your group and see if you can find changes. (Make a note of your changes so you can reset to the Earth composition). Make sure to change your filename to describe what you changed so you can compare. Feel free to use the Tutorial\_Plots.ipynb to plot pressure, temperature and density for your new planets.
   3. Write down what you’ve changed, and some of your observations on how the calculated radius is changing and other aspects of the planetary interior (core radius, pressure at center of core etc.). Once you’ve tried a few different compositions do you notice any trends? Note these down!
   4. If you don’t want to see this plot EVERY time, follow instructions after line that says “#Now let us plot'”, roughly line 171 in MR\_Trappist.py
3. Now that we have a sense of what things can happen, let’s focus on your group’s individual parameter. Begin with TRAPPIST-1 b and assign different team members the other planets.
   1. The cores of planets are often not pure Iron. Instead, other elements are often alloyed with Fe, which makes the core less dense than you’d expect. This in turn, lowers the density of the planet itself and can affect our mass-radius-composition interpretations.
      1. You have access to three different elements to put into your core: O, S and Si.
   2. If you’re proficient in python, you can write a loop to do this for you. If not, you can copy things by hand into the Tutorial\_Plots.ipynb “individual runs” section of the Jupyter notebook. Regardless, run for 10 different wt\_frac\_Si\_core, wt\_frac\_O\_core and wt\_frac\_S\_core, varying only one each time.
      1. Keep track of the resulting radii and your input core weight fractions for each element; these will be used in 7 and 8.
   3. What are you noticing about the mass fraction core reported in the terminal for different weight fractions of each element in the core?
   4. How much of each element do you estimate must segregate into a planetary core in order to change its radius by ~10% for each planet?
   5. Which core chemistry looks like the best fit for each TRAPPIST-1 planet? Write these values down for each T1 planet below (you may not be able to find the best Si content for each planet because you will exceed the compositional grid space).

|  |  |  |  |
| --- | --- | --- | --- |
| Planet | Best-fit Core O content (wt%) | Best-Fit Core S Content (wt%) | Best-Fit Core Si Content (wt%) |
| TRAPPIST-1 b |  |  |  |
| TRAPPIST-1 c |  |  |  |
| TRAPPIST-1 d |  |  |  |
| TRAPPIST-1 e |  |  |  |
| TRAPPIST-1 f |  |  |  |
| TRAPPIST-1 g |  |  |  |
| TRAPPIST-1 h |  |  |  |

1. Note for the following tasks we will only be working with Let’s be more precise with our determination of “best-fit” core chemistry. To do this we will adopt a chi-squared test. We define this test by:
   1. When χ2 ≤ 1, this is considered a good fit. For each of the radii you calculated in 3b, calculate χ2. Either automate this using python, or proceed by hand. Make sure to do this for each T1 planet.
   2. Input these χ2 values into the chi-squared section of Tutorial\_Plots.ipynb. Note to keep track of your x-axis (core Si content) and y-axis (χ2).
   3. You will find MANY compositions produce χ2 ≤ 1. What are the minimum and maximum weight fractions O in core that produce χ2 ≤ 1?
      1. It is also possible to find no amount of variation in your parameter causes χ2 to fall below one. This just means that our model is insensitive to changes in your parameter. Does this mean we can constrain this aspect of a planet’s composition using only mass and radius?
      2. Fill out the table below, and make sure to include it in your talk!
2. Would you say the TRAPPIST-1 planets are consistent with being “Earth-like?”

|  |  |  |
| --- | --- | --- |
| Planet | Min. Core O Content wt% (χ2 ≤ 1) | Max O Core Content wt% (χ2 ≤ 1) |
| TRAPPIST-1 b |  |  |
| TRAPPIST-1 c |  |  |
| TRAPPIST-1 d |  |  |
| TRAPPIST-1 e |  |  |
| TRAPPIST-1 f |  |  |
| TRAPPIST-1 g |  |  |
| TRAPPIST-1 h |  |  |

1. Unfortunately planetary mass has uncertainty that we aren’t accounting for in these above models. In order to account for this we must randomly sample the mass within the observational uncertainty.
   1. Currently Mass\_planet\_sigma (line 40) is set to zero. Change this value to your individual T1 planet’s respective mass uncertainty (available in the comments of MR\_Trappist.py).
   2. Now instead of running a single iteration, let’s run 50 total samplings. Change number\_of\_runs (line 84) to 50.
   3. Currently MR\_Trappist.py is set up to save a file that contains the data produced from all 50 runs. If you’d like to give this file a special name, change Output\_filename (line 82) to whatever you like. Note the code automatically adds “.csv” to the end.
   4. Run MR\_Trappist.py for your planet and maximum and minimum best fit compositions you found above. (100 runs today, 50 for max, 50 for min)
   5. In Tutorial\_Plots.ipynb, upload this datafile and plot the respective histogram.
      1. How much does radius vary for this “best-fit” composition just from the uncertainty in mass? Is this variation larger or smaller than the uncertainty on radius itself?

1. If you have even time, calculate and plot χ2 for each of these 100 runs (same as 5a-c). Did your range of “best fit” compositions expand? If so, how much?

|  |  |  |
| --- | --- | --- |
| Planet | Min. Core O Content wt% (χ2 ≤ 1) | Max O Core Content wt% (χ2 ≤ 1) |
| TRAPPIST-1 b |  |  |
| TRAPPIST-1 c |  |  |
| TRAPPIST-1 d |  |  |
| TRAPPIST-1 e |  |  |
| TRAPPIST-1 f |  |  |
| TRAPPIST-1 g |  |  |
| TRAPPIST-1 h |  |  |